One Hundred Ninety-Five Cases of High-Voltage Electric Injury

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High-voltage electric injury (HVEI) is associated with a high incidence of extremity compartment syndrome and of major amputation. The purpose of this study was to review our experience with HVEI and to attempt to develop predictors of the need for fasciotomy and amputation in patients with HVEI. The records of the 195 patients with HVEI who were admitted to a single burn center during a 19-year period were reviewed. Evidence for muscle necrosis, to include myoglobinuria and elevated creatine phosphokinase (CPK) levels, was noted. A total 187 patients (95.9%) survived to hospital discharge. A total of 56 underwent fasciotomy within 24 h of injury; 80 patients underwent an amputation during the hospitalization. Fasciotomy was predicted by presence of myoglobinuria with an overall accuracy of 72.8%. Amputation was predicted by a logistic model incorporating myoglobinuria, undergoing a previous fasciotomy, and age, with an overall accuracy of 73.3%. HVEI was associated with high amputation risk and a low rate of mortality in patients admitted to our burn center. Patients with gross myoglobinuria are at higher risk of requiring fasciotomy and/or amputation. (J Burn Care Rehabil 2005;26:331–340)

Although present-day therapy has reduced greatly the incidence of acute renal failure and the mortality after high-voltage electric injury (HVEI), this injury is often devastating and features a high amputation rate and long-term rates of morbidity.[1,2] It is well known that in patients with HVEI, the cutaneous burn size does not necessarily reflect the extent of underlying tissue damage or predict outcome. By contrast, the burn size, the age of the patient, and the presence or absence of inhalation injury predict outcomes such as mortality for patients with thermal injury secondary to flame or scald with a high degree of accuracy.[3,8] The purpose of this study was to evaluate our experience with patients who experienced a HVEI and to determine whether factors present on the patient's admission could be used to predict significant outcomes, including the need for fasciotomy and amputation.

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METHODS

The Institutional Review Board of Brooke Army Medical Center approved this retrospective review of existing clinical data. The records of the 4763 patients admitted to the U.S. Army Burn Center between January 1978 and June 1997, a 19-year period, were reviewed. The study was limited to this period because a uniform regimen of care was used throughout. HVEI was defined as contact with 1000 volts or greater. Patients admitted directly to this Center from the field, as well as those admitted from referring hospitals, were included in the study. Patients of all ages were included. Patients whose primary mechanism of injury appeared to be flash or explosion of a high-voltage wire, transformer, or other device, as opposed to direct contact with high voltage, were excluded. Those with lightning injury also were excluded because the mechanism of injury differs from that of HVEI. One hundred ninety-five cases met these criteria and were evaluated.

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A previously described approach to the resuscitation of the patient with HVEI was used during the study period.[4,5] Briefly, all patients with HVEI were admitted to a research-oriented burn intensive care unit. The cutaneous burn size was estimated by means of the Lund-Browder chart. Inhalation injury was diagnosed by fiberoptic bronchoscopy or by xenon-133 lung scanning. Gross pigmenturia was diagnosed visually and was confirmed by urine positive on dipstick test for blood and negative on microscopy for red blood cells. Thus, "myoglobinuria" in this study refers to gross pigmenturia diagnosed in this fashion; a confirmatory urine myoglobin assay was performed infrequently. In addition, serum creatine phosphokinase (CPK) levels often were available. Patients were resuscitated with lactated Ringer's solution according to the modified Brooke formula, and the infusion rate was adjusted to maintain a urine output of 30 to 50 ml/hr in adults. However, patients with gross pigmenturia received additional lactated Ringer's solution, sufficient to produce a urine output of 70 to 100 ml/hr in adults, and the serial appearance of the urine was evaluated. Failure to clear the pigmenturia over several hours was an indication for giving mannitol, usually 12.5 g per liter of lactated Ringer's solution. Also, sodium bicarbonate was frequently used to alkalinize the patients' urine. However, the retrospective nature of this study and the fact that many patients were transferred from other facilities, means that it was not possible for us to ascertain that this resuscitation regimen was followed as described in all cases.

Once resuscitation was underway, patients with clinically evident extremity compartment syndrome or elevated compartment pressures underwent urgent fasciotomy in the operating room. Amputation normally was postponed until resuscitation was complete. Burn wounds were treated with alternating silver sulfadiazine and mafenide acetate creams. Standard criteria were used for the diagnosis of infection.[6]

There is no index available for HVEI, analogous to burn size for thermal injury, that allows one to quantify the severity of injury. In an effort to address this shortcoming, we generated an index to provide an estimate of the total volume of tissue lost through amputation during the hospital stay. This variable, "PATHINDEX," was defined as the percentage of the body surface area lost secondary to amputation. It was derived from the body surface area estimates provided by the Lund–Browder chart. For example, the loss of one foot and one leg by means of a through-the-knee amputation gave a patient a PATHINDEX of 10.5 because the foot occupies 3.5% of the TBSA on the Lund–Browder chart and the leg 7.0%. (The loss of digits alone did not contribute to the index.)

We sought to identify patients who had sustained significant skeletal muscle damage by means of four variables. These were the presence of gross pigmenturia ("myoglobinuria"), an elevated serum CPK level ("elevated CPK"), an attempt to alkalinize the urine by the intravenous administration of sodium bicarbonate ("alkalinization"), and the use of mannitol ("mannitol"). We then defined a summary variable, "MMDAMAGE," whose value was positive if any of the aforementioned four variables was positive. We separately recorded the performance of a fasciotomy during the first 24 hours after burn injury ("fasciotomy"). We also recorded the maximum CPK level reached (MAXCPK).

Analyses were performed with SPSS software (SPSS Institute, Chicago, IL) or in Microsoft Excel (Microsoft, Redmond, WA), except where indicated. Descriptive values are given as proportions (%) or as means ±SD. Medians and interquartile ranges (IQRs) also are provided for selected non-normally distributed data. Normality of continuous variables was assessed using the Kolmogorov–Smirnov and Shapiro–Wilk tests. Normally distributed data were analyzed by independent-samples *t*-test (assuming or not assuming equal variances, as necessary, based on Levene's test). Non-normally distributed data were normalized by $\log_{10}$-transformation before analysis if possible or, if not, were analyzed by using Mann–Whitney *U* test. Categorical data were analyzed by χ^2 test or by the two-sided Fisher's exact probability test if an expected cell count was less than five.

Logistic regression (backward likelihood-ratio method) was used to select, from among the independent variables (identified by univariate testing), those contributing simultaneously and significantly to the occurrence of fasciotomy and of amputation. In addition, logistic regression was used to model and evaluate the prediction of amputation risk. To evaluate amputation predictions from the final logistic model, we noted that a logistic solution P (predicted probability) above a chosen P cutpoint predicted "yes" for amputation in a given patient (otherwise "no"). The P cutpoint (0.4) was chosen to yield similar sensitivity and specificity and to give similar frequencies for the event and prediction of the event.

After overall analysis of the 195 patients, we assessed the internal validity of the equation predicting amputation. The patients were divided randomly into two groups. This allowed us to assess the ability of the logistic model for amputation—with new coefficients for the predictor variables calculated on the basis of the patients in one group—to predict the respective

event in a group not contributing to model development. At first, group 1 (n = 98) was the training group in which a logistic predictor equation was developed and applied to its members to predict "yes" or "no" for the event. The other patients (group 2, n = 97) served as the validation group, with the same equation used to predict the event for its members. Then the process was reversed by switching the training and validation groups. The P cutpoint of 0.4 was used throughout. Logistic analysis itself does not test discriminative ability of the logistic prediction in a group not contributing to development of the model (a validation group), nor does it compare that ability between such a group and another group. Thus, receiver-operating-characteristic (ROC) analysis (DeLong empiric method) was used[7] for these purposes. Using the ROC analysis, we tested the ability of a logistic equation to discriminate between occurrence and nonoccurrence of amputation: 1) in each of the two groups (no discrimination being represented by the null ROC area under the curve = 0.5); and 2) for a difference in discrimination (area under the curve) between training and validation groups.

RESULTS

The mean age of the group was 27.9 ± 11.5 years (median, 25.0; IQR, 14.0; range, 2–78), and 25 patients (12.8%) were younger than the age of 18. Almost all of the patients (189, or 96.9%) were men. For those 82 cases for which the precise voltage was recorded, 10 (12.2%) were exposed to 1000 to 7000 volts, 27 (32.9%) to 7200 volts, and 45 (54.9%) to more than 7200 volts. The mean TBSA was 17.5 ± 16.9% (median, 12.5; IQR, 22.0), and the mean full-thickness burn size (FULL) was 9.7 ± 12.3% (median, 4.0; IQR, 12.0). 5.6% of the patients sustained inhalation injury. The in-hospital survival rate was 95.9%.

One hundred twelve patients (57.4%) were injured at work. Forty-four (39.3%) of those injured at work were working on power lines or doing other electrical work. Patients injured at work were slightly older (30.3 ± 9.8 years) than those injured elsewhere (25.0 ± 12.9 years, $P = .001$). Fifty-seven patients (29.2%) were active duty military personnel. This group included 30 patients injured at work, and 27 patients injured during nonwork activities. Twelve patients (6.2%), all of them military personnel, sustained HVEI during parachute operations; 3 of the 12 jumps were recreational. Four of 9 jumps (44%) for which data were available in our series took place at night.

One hundred eleven patients (56.9%) were injured in the state of Texas, 65 (33.3%) elsewhere in the United States, and 19 (9.7%) overseas. Most (86.2%) were transferred to this Center from other hospitals; 85 patients (43.6%) were aeromedically evacuated by this Center's Burn Flight Team. Transfer to this Center was, in most cases, rapid: 49.7% of all patients were admitted to this center on the day of injury, 21.5% the next day, 9.4% the second day after burn injury, and 19.4% on the third day after burn injury or thereafter. (We were not able to find a difference between patients directly admitted to the burn center and those transferred from elsewhere with respect to severity of injury [TBSA, age, voltage, PATHINDEX, myoglobinuria, MAXCPK], procedures performed [fasciotomy, amputation, alkalinization, mannitol, delay in amputation], year injured, age, or survival [data not shown].)

Loss of consciousness at the scene, with or without cardiac arrest, occurred in 63 patients (32.3%), of whom 14 (7.2% of the total) sustained apparent cardiac arrest immediately after contact with the high-voltage source. Because documentation was not complete in all cases, we defined cardiac arrest as loss of consciousness with the performance of cardiopulmonary resuscitation. Nonburn injuries were sustained at the time of electric injury by 49 patients (25.1%). These injuries are summarized in Table 1. Of these, the most common were fractures in 22 patients, soft-tissue lesions in 14, lung injuries in 9, and head injuries in 8.

In addition to the aforementioned 14 patients

Table 1. Associated trauma

A total of 49 of 195 (25.1%) sustained the following associated acute injuries
Fracture: 22
Skull: 4
Cervical spine: 2
Thoraco–lumbar spine: 5
Upper extremity (including two scapular fractures): 7
Rib: 1
Femur/acetabulum: 1
Tibia/fibula/ankle/foot: 5
Soft-tissue injury (laceration, contusion, hematoma): 14
Lung injury (pneumothorax, contusion): 9
Brain/head injury (subdural hematoma, intraparenchymal hemorrhage, concussion, basilar skull fracture, anoxic brain injury): 8
Acute ocular injury (acute iritis, subconjunctival hemorrhage, corneal abrasion, corneal foreign body): 6
Nonfracture orthopedic injury (sprain, open joint): 3
Renal injury (hematoma, contusion): 2
Intra-abdominal injury (spleen, large bowel, small bowel): 2

who went into cardiac arrest at the scene, 3 other patients went into cardiac arrest during the first 24 h after burn injury. In all, 82.4% of the 17 patients who went into cardiac arrest during the first 24 hours survived to hospital discharge. Characteristics of the first 24 hour after burn injury are listed in Table 2. Of the various indicators of muscle damage, myoglobinuria was reported most frequently (63 patients, 32.3%).

Fasciotomy

Fifty-six patients (28.7%) underwent a fasciotomy within 24 hours of injury. Results of univariate analysis of the association of various factors with fasciotomy are presented in Table 3. Of the various factors associated with muscle damage (elevated CPK, myoglobinuria, alkalinization, mannitol), only myoglobinuria was included in this analysis because fasciotomy usually is performed at this Center within hours of admission, and myoglobinuria, but not the other data, usually can be assessed immediately upon admission. The univariate analysis showed that TBSA, FULL, and myoglobinuria were associated with fasciotomy. These three variables were submitted to logistic regression, which retained myoglobinuria but rejected FULL and TBSA. That is, only myoglobinuria contributed significantly ($P < .001$) to the variability in occurrence of fasciotomy. Therefore, the predicted probabilities (logistic P in the final model) could have only two values uniquely identifying patients with and without myoglobinuria, giving back only the same information as in the univariate relationship of myoglobinuria to fasciotomy ($P = .001$, χ^2 and Fisher's exact probability tests). Of the 56 with fasciotomy, 33 had myoglobinuria, whereas of the 139 without fasciotomy, 109 did not have myoglobinuria. Thus, myoglobinuria had observed sensitivity of 58.9%, specificity of 78.4%, and overall accuracy of 72.8% for predicting occurrence of fasciotomy in the first 24 hours after electric injury.

Table 2. Events during the first 24 hours after burn injury

Variable	Number	Percentage
Elevated CPK	58	29.7
Myoglobinuria	63	32.3
Alkalinization	29	14.9
Mannitol	40	20.5
MMDAMAGE	102	52.3
Fasciotomy	56	28.7
Mechanical ventilation	37	19.0
MAXCPK (mean ± SD)	20,829 ± 40,930 (median, 3,910; IQR, 18,417)	

CPK, creatine phosphokinase; *MAXCPK*, mean of the maximum CPK (U/l), calculated for patients with elevated CPK only; *MMDAMAGE*, presence of any of the following: elevated CPK, myoglobinuria, alkalinization, or mannitol.

Amputation

Eighty patients (41.0%) sustained an amputation during this hospitalization. Repeated visits to the operating room for amputation were experienced by 27 patients (33.8% of amputation patients). Results of univariate analysis of the association of various factors with amputation are presented in Table 4. Upon admission, age, TBSA, and FULL were associated with performance of amputation during this hospitalization. During the first 24 hours after burn injury, myoglobinuria, mannitol, elevated CPK, MAXCPK, MMDAMAGE, and fasciotomy were each associated with amputation during the hospitalization.

We then performed logistic regression, submitting those variables significantly associated with amputation risk by univariate analysis. The model retained fasciotomy, myoglobinuria, and age as independent predictors of amputation ($P < .001$, $<.001$, and .002, respectively). That is, each of these variables contributed significantly to the variability in occurrence of amputation, with simultaneous accounting for the contribution of the others. See Figure 1 to visualize the occurrence of amputation according to fasciotomy, myoglobinuria, and age. The predicted probability of amputation is given by the following equation:

$$P = e^k/(1 + e^k),$$

$$\text{where } k = -2.78 + 1.99{*}\text{fasciotomy} + 1.56{*}\text{myoglobinuria} + 0.0462{*}\text{age}.$$

In this equation, fasciotomy and myoglobinuria are categorical variables each with values of 0 or 1, and age is a continuous variable. For this predictive model, the sensitivity was 73.8%, specificity 74.8%, and overall accuracy 74.4% (n = 195, Nagelkerke $r^2 = 0.39$, P cutpoint = 0.4). The prevalence of amputation prediction (88/195 = 45.1%) was close to the prevalence of amputation (80/195 = 41.0%). Of the 80 patients with amputation, 59 were predicted; and of the 115 without amputation, 86 were predicted not to have amputation. ROC area under the curve was 0.810 ($P < .001$ vs. no discrimination).

ROC analyses indicated that further logistic models for amputation, developed in one randomly defined training group of the patients but applied to the other (validation) group maintained significant abil-

Table 3. Factors associated with fasciotomy

Variable	Fasciotomy	No fasciotomy	*P* value
Age	27.6 ± 9.3	28.1 ± 12.3	.755
TBSA	20.2 ± 16.6	16.4 ± 16.9	.026*
FULL	12.7 ± 11.7	8.5 ± 12.3	<.001*
Inhalation Injury	1.8%	7.2%	.139
Voltage	16,523 ± 21,103	13,803 ± 16,971	.577*
Fracture	8.9%	12.2%	.510
Other trauma	21.4%	19.4%	.752
Myoglobinuria	58.9%	21.6%	<.001

TBSA, total burn surface area (% body surface); *FULL*, full-thickness burn, % body surface area; *Other trauma*, injury other than a fracture.
Values are mean ± SD or percent of group. Age, age in years.
* Mann–Whitney *U* test.

Table 4. Factors Associated with Amputation

Variable	Amputation	No amputation	*P* value
Upon admission			
Age	30.3 ± 12.5	26.3 ± 10.5	.018
TBSA	18.3 ± 14.3	16.9 ± 18.4	.038*
FULL	12.4 ± 11.4	7.8 ± 12.6	<.001*
Inhalation Injury	3.8%	7.0%	.340
Voltage	18,093 ± 23,332	12,287 ± 13,514	.270*
Fracture	9.8%	11.3%	.991
Other trauma	21.3%	19.1%	.716
During first 24 hours after burn injury			
Elevated CPK	37.5%	24.3%	.048
MAXCPK	29,650 ± 44,445	11,330 ± 35,174	.002†
Myoglobinuria	55.0%	16.5%	<.001
Alkalinization	20.0%	11.3%	.093
Mannitol	32.5%	12.2%	.001
MMDAMAGE	68.8%	40.9%	<.001
Fasciotomy	53.8%	11.3%	<.001
Mechanical ventilation	23.8%	12.2%	.156

TBSA, total burn surface area (% body surface); *FULL*, full-thickness burn, % body surface area; *Other trauma*, injury other than a fracture. *CPK*, creatine phosphokinase; *MAXCPK*, mean of the maximum CPK (U/l), calculated for patients with elevated CPK only; *MMDAMAGE*, presence of any of the following: elevated CPK, myoglobinuria, alkalinization, or mannitol.
Values are mean ± SD or percent of group. Age, age in years.
* Mann–Whitney *U* test.
† Analysis performed on $\log_{10}$-normalized data.

ity to discriminate occurrence of amputation ($P <$ .001). This was true regardless of which group was used as the training group to develop the model. In addition, with ROC analysis, no difference was detectable in discriminative ability between application of a logistic model to the training group in which it was developed and application to the validation group not contributing to the model, regardless of which of the two random groups was used as the training group. These results support the notion that the relationships uncovered by logistic regression represent real effects in the entire data set (internal validity).

We also assessed the timeliness of amputation. For the 56 amputation patients for whom the date of the first amputation was available, 20 (35.7%) underwent their first amputation within 2 days of injury, 18 (32.1%) within days 3 to 7 of injury, and 18 (32.1%) on day 8 or thereafter. However, considering only those 49 patients with a large volume of tissue loss (ie, with PATHINDEX > 0), 19 (51.4%) underwent their first amputation within 2 days of injury, 10 (27.0%) within days 3 to 7 of injury, and 8 (21.6%) on day 8 or thereafter.

We used the PATHINDEX to describe the volume of tissue lost secondary to amputation and deter-

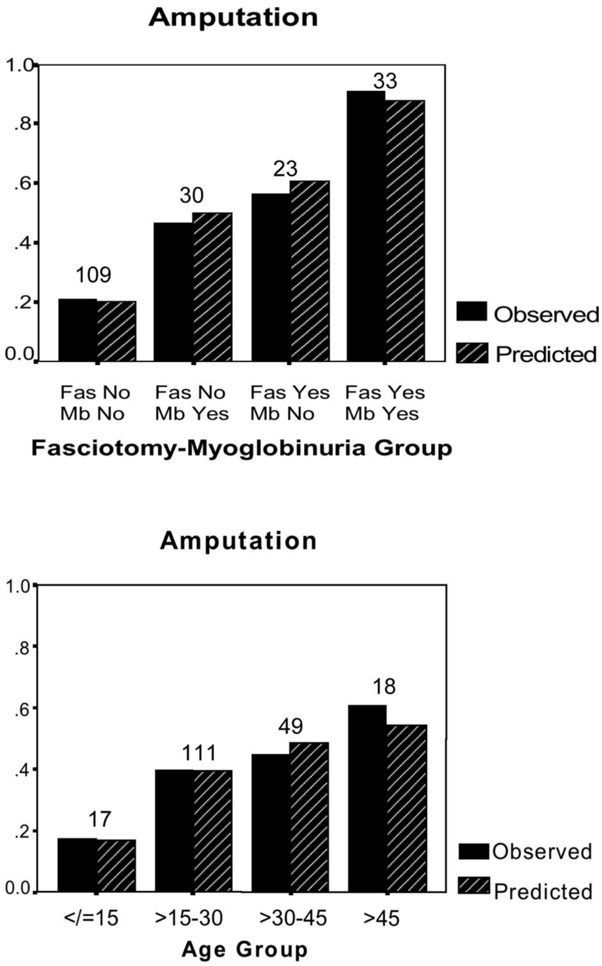

Figure 1. Occurrence of amputation according to grouping of the 195 patients by fasciotomy (Fas) and myoglobinuria (Mb) in the upper panel and by age in the lower panel. The denominator (number of patients) in each group is indicated above the bars. The predicted frequency for a given group is from the logistic equation, simultaneously accounting for all three factors. The equation was solved for each patient in a group, the predicted probabilities summed to obtain the number of patients with amputation predicted for the group, and the latter divided by the number of patients in the group.

mined those factors associated with an increased PATHINDEX. The mean PATHINDEX for patients sustaining an amputation (and excluding those who underwent amputation of digits only, for whom PATHINDEX=0) was 12.4 ± 6.7%. The PATHINDEX was higher in amputation patients with associated trauma other than fractures ($P = .021$), myoglobinuria ($P < .001$), mannitol ($P < .001$), MMDAMAGE ($P < .001$), and fasciotomy ($P < .001$). However, PATHINDEX in amputation patients was not significantly associated by linear regression with voltage ($r^2 = .077$, $P = .105$, n = 35), MAXCPK ($r^2 = .045$, $P = .279$, n = 28), FULL ($r^2 = .047$, $P = .054$, n = 80), TBSA ($r^2 = .027$, $P = .142$, n = 80), or age ($r^2 = .018$, $P = .230$, n = 80). Aside from amputation, fasciotomy, and skin grafting, other operations were performed, including complex plastic surgical procedures for soft-tissue coverage in 33 patients (16.9%).

Morbidity and Mortality

Eight patients (4.1%) did not survive to hospital discharge. The median day of death for these patients was 4 (range, 1–19, IQR 8.8) days after burn injury. Causes of death are listed in Table 5; most deaths were directly attributable to the magnitude of tissue damage and/or direct myocardial injury.

Complications diagnosed during the hospitalization are listed in Table 6. Despite the high incidence of myoglobinuria, acute renal failure was uncommon, occurring in only 6 patients (3.1%). Myoglobinuria was present in four of these six patients. All patients with acute renal failure died (Table 5).

Sixteen patients sustained acute ocular injuries or subacute ocular complications, of which the most common were corneal lesions in seven patients; these included corneal abrasions, exposure keratitis, and corneal ulcers. Three patients developed cataracts during the acute hospitalization. Because long-term follow-up of these patients did not occur, the true

Table 5. Cause and time of death

Cause	Postburn Day of Death	Renal Failure
Hyperkalemia secondary to massive muscular necrosis	1	Yes
Cardiac failure secondary to direct myocardial electric injury	1	Yes
Acute respiratory distress syndrome secondary to injury	2	No
Hyperkalemia, abdominal compartment syndrome	2	Yes
Multiple system organ failure, etiology uncertain	6	Yes
Hypoxic encephalopathy secondary to cardiopulmonary arrest at time of injury	7	No
Aspiration pneumonia, sepsis, invasive wound infection (yeast)	11	Yes
Invasive burn wound infection (*Pseudomonas* and fungus)	19	Yes

Table 6. Complications occurring during hospitalization

Variable	Number	Percentage
Acute renal failure	6	3.1
Infections		
Burn wound cellulitis	31	15.9
Bacteremia	20	10.3
Pneumonia	11	5.6
Invasive burn-wound infection	6	3.1
Neurologic		
Peripheral nerve injury	29	14.9
Ocular complications	10	8.2
Spinal cord injury	5	2.6

Ocular complications: excludes eye injuries occurring at the time of burn (Table 1).

incidence of cataract formation in these patients was not determined.

Five patients developed spinal cord lesions. In two cases, these were secondary to spinal fractures occurring at the time of injury: T10 paraplegia secondary to a burst fracture at that level; and T4 to T5 paraplegia, secondary to fractures of T4 to T7. In 3 cases, fractures were not present: one case of a T11 to T12 sensory deficit; one case of cervical myelitis; and one other case of paraplegia. Twenty-eight patients (14.4%) developed a peripheral nerve deficit of acute or delayed onset during the hospitalization. They included 13 lesions of the ulnar nerve, 10 of the median nerve, 9 of the radial nerve, and 5 of the common peroneal nerve.

DISCUSSION

The principal findings in this study of patients with HVEI are as follows: 1) the diagnosis of compartment syndrome, resulting in the performance of a fasciotomy, was predicted by the presence of myoglobinuria; 2) amputation risk was independently increased by the presence of myoglobinuria, the need for fasciotomy, and older age; and 3) the severity of injury, as estimated by the volume of tissue lost by amputation (PATHINDEX), was higher in patients with myoglobinuria.

These findings should be interpreted with caution. The sensitivity and specificity values reported here are too low to replace clinical judgment in the decision to perform fasciotomy or amputation. Thus, the presence of myoglobinuria should not mandate operation, nor should its absence mandate nonoperative therapy. Furthermore, use of our logistic predictor equation for amputation after HVEI in patients outside the sample studied, for instance, from other institutions, would involve limitations related to external validity always inherent in a single retrospective study. In the future, larger samples might be studied to uncover other predictor variables for amputation or might alter the estimated strength (coefficients) of the predictor variables retained in our model. Rather, the main utility of these findings may be to increase the index of suspicion that surgery will be required when myoglobinuria is present. This information also may assist providers in counseling patients and their families and in selecting patients for diagnostic studies, if desired.

Another limitation of this study is its retrospective nature. Furthermore, most patients were transferred to this center from other hospitals, although transfer was usually timely. To circumvent these shortcomings, we recorded several variables indicative of severe muscle injury to include two (alkalinization and use of mannitol) that were based on provider behavior. Indeed, it could be argued that use of these variables is potentially flawed because provider behavior during resuscitation was not necessarily standardized with respect to the decision to use mannitol and/or bicarbonate. Possibly reflecting this inconsistency, neither of these two variables was retained in the multivariate predictor of amputation risk. By contrast, those variables that were retained by this predictor (fasciotomy, myoglobinuria, and age) are objective and, we believe, are highly likely to be recorded if present. Specifically, fasciotomy was not performed at this center prophylactically but only in the presence of extremities with obvious compartment syndrome and/or elevated compartment pressures. Myoglobinuria, because it dramatically alters the resuscitation regimen, is also highly likely to be recorded in the patient record. On the other hand, we are less confident in the fidelity with which the maximum CPK level was recorded, because a standard protocol for measuring this value was not in place.

Although the ages in the 195 patients ranged from 2 to 78 years, 50% of the patients were between 20 and 34 years (the interquartile range), 80% between 16 and 45, and 90% between 12.5 and 51.1. Caution is indicated for the use of our present logistic model in young children and the elderly. For further discussion of this matter, please see the Appendix.

The use of logistic models is best restricted to predicting the number of events in groups of patients for research and comparative purposes, rather than predicting an event for a single individual. For application outside our original data set, the predictive value of a positive test (PVPT, probability of amputation if the prediction is "yes") and of a negative test (PVNT, probability of no amputation if the prediction is "no") are highly dependent on the pretest probability

(PRE, the true prevalence or probability of the event in a population with characteristics defined by those patients who would actually be tested). For groups, PRE can be estimated from the data. However, predicting the outcome of a single individual often is hampered by greater uncertainty of PRE, as well as diminished usefulness of the PVPT or PVNT when not very close to 1 or 0. For amputation, with the PRE inherent in the present data set (80/195 = 0.410), PVPT = 67.1%, and PVNT = 80.4%. However, corrected for use in other patients, these values could be, for instance, PVPT = 24.5% and PVNT = 96.3% if the correct PRE be 0.1, and PVPT = 96.3% and PVNT = 24.0% for a PRE of 0.9. The cited theoretical values of PRE (0.1 and 0.9) are only examples, and other values would likely apply. The formulas for these post-test probabilities are as follows:[9]

$$\text{PVPT} = (\text{PRE} \times \text{sensitivity})/[(\text{PRE} \times \text{sensitivity}) + ((1 - \text{PRE}) \times (1 - \text{specificity}))], \text{ and}$$

$$\text{PVNT} = [(1 - \text{PRE}) \times \text{specificity}]/[((1 - \text{PRE}) \times \text{specificity}) + (\text{PRE} \times (1 - \text{sensitivity}))].$$

Other findings of note in HVEI were the low rate of acute renal failure; the high rate of on-the-scene cardiac arrest with excellent survival; and the high incidence of concomitant orthopedic, ocular, neurologic, and reconstructive problems, mandating a multidisciplinary approach to patient care. PATHINDEX, a new index of the severity of HVEI based on the volume of tissue lost because of amputation, was higher in patients with several indicators of a more severe injury, to include myoglobinuria. The clinical utility or relevance of this index remains to be determined.

DiVincenti et al,[10] also from this burn center, reported 65 cases of electric injury for the period 1950 to 1968, of which 53 were high-voltage. A comparison of this to the present study is presented in Table 7. Of note, both the mortality rate and the acute renal failure rate decreased. These rates also has been observed in other centers. DiVincenti et al[10] noted that acute renal failure, seen in seven patients, was associated with pigmenturia after injury. It is likely that improvements in the resuscitation of these patients, directed towards maintenance of high urine outputs and the use of mannitol and sodium bicarbonate, have served to decrease the renal failure rate. This attests to the value of the simple, visual guide (pigmenturia).

The pathophysiology of electric injury is not completely understood. However, cell death after injury is most likely the result of three processes: Joule heating, electroporation, and electroconformational protein degradation. Joule heating refers to the generation of heat by the movement of current through a resistor. Electroporation is a process by which electrical dipoles, such as water molecules, are pulled by the electrical field into the cell membrane. If this generates pores whose diameter is sufficient to favor pore stabilization rather than closure, permanent defects result that lead to cell death. Finally, electroconformational protein degradation refers to a process by which the cell-membrane proteins comprising voltage-gated ion channels, such as potassium channels, are damaged by electrical fields.[11,12]

The electroporation concept may explain the phenomenon known as "progressive recognition." Frequently, muscle tissue that appears viable at first exploration is found, on subsequent operations, to have become necrotic. It appears unlikely that this damage

Table 7. Complications of high-voltage electric injury in several series

Author	Location of Institution	Years Covered	No. Patients	Died, %	Amputation, %	Renal Failure, %
DiVincenti[10]	San Antonio; U.S. military	1950–1967	53	19	33	13
Rai[1]	Galveston	1967–1997	58 children	0	33	0
Yan[21]	Shanghai	1972–1998	836†	1	23	1
Hunt[2]	Dallas	1973–1978	102	2	25	0
Cancio*	San Antonio; U.S. military	1978–1997	195	4	41	3
Haberal[22]	Turkey	1980–1985	94‡	59	27	18

* The current study.
† Includes 568 patients with high-voltage injury.
‡ Includes high and low voltage.

is caused by operator error or treatment-induced damage because several experimental studies have demonstrated that it indeed is possible to induce lethal cell damage without an immediate change in gross tissue appearance.[12] Regardless of the pathophysiology, this syndrome indicates the wisdom of at least one planned re-exploration, approximately 48 hours after initial débridment. In this study, we did not quantify the presence of "progressive recognition." However, a sense of the magnitude of the problem can be gained by noting that 33.8% of amputation patients required more than one operative episode for amputation.

Another common finding is the presence of necrotic periosseous muscle, extending proximally in a limb beneath normal appearing muscle; this mandates careful inspection of the deepest muscle groups in patients who undergo exploration. No entirely satisfactory explanation for this has been advanced, although it has been noted that the heat capacity of bone is higher, such that in remains hot longer. This likely causes more severe thermal damage to periosseous tissues.[13,14] In light of this, we make an effort to explore periosseous muscles in affected extremities.

Several diagnostic techniques have been used to assist in the detection of necrotic muscle after electric injury. Hunt et al[14] in animal models demonstrated arteriographically that electric injury can cause immediate thrombosis of major arteries. In a clinical series, they found that complete or partial arterial thrombosis predicted a need for amputation, albeit often at a higher level than that of the occlusion. However, patent vessels were consistent with a low incidence of necrosis.[13] Technetium-99 pyrophosphate, which shows increased uptake in areas in which approximately 20% to 60% necrosis has occurred and which shows no uptake in completely necrotic limbs, has been used by several centers to plan operative intervention.[15,16] Lee et al[12] have recommended the use of magnetic resonance imaging as soon as possible after patient arrival to identify edematous muscle compartments. This information is used to guide compartment pressure measurements. In our practice, serial neurovascular examinations, and measurement of compartment pressures in edematous limbs, are the primary diagnostic modalities currently used to screen in patients without an obvious immediate need for fasciotomy.

Levine et al[17] reported spinal injury, without fracture or other mechanical trauma, in 2 of 111 patients admitted to this center during a 21-year period. They noted that such deficits, when they appear immediately after injury, may be transient, whereas in other cases deficits may present days, months, or even years later and may be permanent. The clinical presentation may be that of ascending paralysis, amyotrophic lateral sclerosis, or transverse myelitis. The incidence of spinal injury in our study was similar. Limited long-term follow-up of the patients in our study does not allow us to comment on whether the spinal and peripheral nerve lesions were temporary or permanent.

Grube et al[18] reported loss of consciousness in 29 of 64 (45%) of patients with HVEI. Most (23 patients, 79%) recovered by the time of arrival to the emergency department and had no known neurological sequelae. In the present study, loss of consciousness was also common after injury, reported for 32.3% of patients.

Occupational electric injury is the fifth leading cause of workplace mortality in the United States and is particularly common in certain industries, such as the construction, manufacturing, and power industries.[19,20] Indeed, most of the injuries in our study (57.4%) were work-related. These data indicate the need for continuing efforts at prevention of electric injury at the workplace. However, HVEI constitutes a minority of admissions to burn centers annually; accordingly, there has been less research performed in this area than in thermal injury. Progress in this field may be accelerated by multicenter studies facilitated by national organizations such as the American Burn Association.

The present study is unique in that 12 patients (6.2%) sustained HVEI during parachute operations. This series constitutes the largest of such injuries reported to date; the previous study from this center by DiVincenti et al[10] described five such cases. All of the patients injured in this manner in our study were military personnel, although 3 of the 12 jumps were performed at sport parachuting clubs. Four of 9 jumps (44%) for which data were available in our series took place at night, indicating the likely roles of decreased visibility in these accidents. Electric injury is a known hazard in both military and sport parachuting, and procedures are in place to identify and deactivate or avoid high-tension wires during parachute operations. Fortunately, these injuries are rare. An inquiry of the civilian sport organization, the U.S. Parachute Association, revealed one electric injury for the 3-year period 1996–1998, whereas approximately 3.25 million sport jumps were made per year during the same period (Glenn Bangs, Director of Safety and Training, personal communication).

CONCLUSION

This study documents the high survival rate, low incidence of acute renal failure, and high incidence of com-

partment syndrome and of amputation after HVEI. Clinical evidence of massive muscle necrosis, manifested by myoglobinuria, may indicate the need for fasciotomy and may predict amputation. The presence of multiple other problems, including fractures, neurological injuries, ocular injuries, and complex reconstructive and rehabilitative needs, underscores the importance of a coordinated multidisciplinary approach to this injury.

APPENDIX

As stated previously, caution is indicated for the use of the equation predicting amputation in young children and the elderly because most of the patients were young adults. However, if we restrict the range of an age comparison to age 45 (10% of the patients were older) vs age 16 (10% of the patients were younger), we can obtain estimates of the effect size for age (odds ratio [OR] and risk ratio or relative risk [RR]) derived from the logistic coefficients listed. The OR is sensitive only to the width of the age range whose limits are compared (not the specific ages involved) and is not altered by the status of the other predictor variables, provided these are set at the same value for both ages being compared. OR for age (odds of amputation at age 45 divided by the odds at age 16) is 3.82 (95% confidence interval 1.59–9.14). Such an OR might be compared with those simultaneously determined for fasciotomy (7.28) and myoglobinuria (4.77), both of these being odds of amputation with the respective event divided by the odds without it, each determined while keeping the other predictor variables at the same value. The RR comparing two values of age, obtained by solving the logistic equation separately for both ages at a given pattern of the other predictor variables, is sensitive to the specific ages cited and depends on the specific values set for fasciotomy and of myoglobinuria. RR for age (computed probability or risk of amputation at age 45 divided by the risk at age 16) is 1.61 if fasciotomy had occurred without previous myoglobinuria, 1.84 if myoglobinuria had occurred without subsequent fasciotomy, 1.16 if both had occurred, and 2.89 if neither had occurred. The influence of age appears respectable, particularly without occurrence of fasciotomy or myoglobinuria.

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